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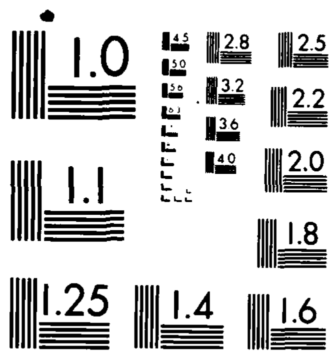

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Effect of Finite Current Channel Width on the Collisional Ion Cyclotron Instability

J. D. HUBA AND P. K. CHATURVEDI

Geophysical and Plasma Dynamics Branch
Plasma Physics Division

AD-A162 070

November 21, 1985

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The effect of a finite transverse width, magnetic field-aligned current on the collisional ion cyclotron instability is studied. It is found that a finite current width has a stabilizing influence on the instability. The results are discussed in the context of auroral ionosphere.

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CONTENTS

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EFFECT OF FINITE CURRENT CHANNEL WIDTH ON THE COLLISIONAL ION CYCLOTRON INSTABILITY

I. INTRODUCTION

It is well known that an equilibrium magnetic field-aligned current can result in the growth of obliquely propagating electrostatic ion-cyclotron waves in collisionless [Drummond and Rosenbluth, 1962] and collisional [Milic', 1972; Chaturvedi and Kaw, 1975] plasmas. This instability has extensively been investigated in the laboratory machines [D'Angelo and Motley, 1962; Cartier et al., 1985], and is believed to have been observed in the auroral ionosphere [Kelley et al., 1975; Yau et al., 1983; Fejer et al., 1984]. The linear and nonlinear theory of this instability applied to the auroral ionosphere is also well developed [Kindel and Kennel, 1971; Chaturvedi, 1976; Satyanarayana et al., 1985]. The field-aligned currents in the auroral ionosphere are an integral part of the ionosphere-magnetosphere coupling system and it is fairly well established now that these currents can be highly nonuniform in structure [Burke et al., 1983; Bythrow et al., 1984]. Often, the current system is in the form of sheets which have variable thicknesses. Earlier efforts to study the oscillation modes of the finite current sheets included those by Elliott [1975] and Dungey and Strangeway [1976]. An attempt to study the effect of finite width of a current sheet on the current driven collisionless ion acoustic instability was made by Hwang et al. [1983] with applications to the auroral situation. They found that the finite thickness of a current sheet results in partially stabilizing the system and contributes to the coherence of the excited waves. Bakshi et al. [1983] have studied the problem of finite width currents on the collisionless current driven ion cyclotron instability and found that for

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sufficiently narrow current channels the mode is stabilized (for L_w < few ρ_i where L_w is the width of the current channel and ρ_i is the mean ion Larmor radius). In this paper we investigate the effects of a finite width current channel on the collisional ion cyclotron (CICI) instability. We find that the instability can also be stabilized for sufficiently narrow current channels.

The organization of the paper is as follows. In the next section we present the basic assumptions and the derivation of the mode equation. In Section III we present an analysis of the mode equation, both analytical and numerical. In the final section we summarize the results and discuss applications of the theory to laboratory and space plasmas.

II. DERIVATION OF THE MODE EQUATION

The geometry and plasma configuration used in the analysis is shown in Fig. 1. The ambient magnetic field is uniform and in the z-direction $\left(\underset{\sim}{B} = B_0 \hat{e}_z\right)$, while equilibrium current is non-uniform in the x-direction and is directed in the z-direction $\left(\underset{\sim}{J} = J_0(x) \hat{e}_z\right)$. The current is assumed to be carried by the electrons. The density and temperature are taken to be homogeneous. For simplicity, we consider cold ions ($T_i = 0$). Also, we consider a weakly collisional plasma in the sense that ν_{ei}, $\nu_{en} \ll \Omega_e$ and ν_{ie}, $\nu_{in} \ll \Omega_i$ where ν_{ab} represents the collision frequency between species a and b.

The basic equations used in the analysis are continuity, electron and ion momentum transfer and current conservation:

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot \left(n_\alpha \underset{\sim}{v}_\alpha\right) = 0 \tag{1}$$

$$0 = -\frac{e}{m_e}\left(\underset{\sim}{E} + \frac{1}{c}\underset{\sim}{V}_e \times \underset{\sim}{B}\right) - \frac{T_e}{m_e}\frac{\nabla n}{n} - \nu_{en}\underset{\sim}{V}_e + \frac{\underset{\sim}{R}_e}{m_e n} \tag{2}$$

$$\frac{d\underset{\sim}{v}_i}{dt} = \frac{e}{m_i}\left(\underset{\sim}{E} + \frac{1}{c}\underset{\sim}{V}_i \times \underset{\sim}{B}\right) - \nu_{in}\underset{\sim}{V}_i + \frac{\underset{\sim}{R}_i}{m_i n} \tag{3}$$

$$\nabla \cdot \underset{\sim}{J} = \nabla \cdot \left[en\left(\underset{\sim}{V}_i - \underset{\sim}{V}_e\right)\right] = 0 \tag{4}$$

where

$$\underset{\sim}{R}_e = - \underset{\sim}{R}_i = - m_e n_e \nu_{ei}\left(\underset{\sim}{v}_e - \underset{\sim}{v}_i\right)$$

and $\alpha = e, i$ for electrons and ions, respectively. The rest of the symbols have their usual meanings. The electron fluid is assumed to have an equilibrium drift velocity, in the z-direction and is non-uniform in the x-direction, i.e., $\underset{\sim}{V}_0 = V_0(x)\,\hat{e}_z$. The zero-order current is expressed as

$$\underset{\sim}{J}_0(x) = - n_0 e\, V_0(x)\,\hat{e}_z \tag{5}$$

where we take

$$V_0(x) = V_0 \exp\left(- x^2/L_w^2\right) \approx V_0\left(1 - x^2/L_w^2\right) \tag{6}$$

Here we have used a parabolic representation of the finiteness of the current along the x-axis, which is an approximation for the normal distribution with a half-width of L_w.

The standard procedure is followed in carrying out the linear stability analysis. The plasma quantities are split into equilibrium and perturbation parts, $f_\alpha = f_{0\alpha} + \delta f_\alpha$, and the perturbed quantities are

assumed to vary as $\delta f_\alpha(x) \sim \delta f_\alpha(x) \exp\left(ik_y y + ik_z z - i\omega t\right)$. The perturbed ion and electron equations of continuity and momentum transfer are combined to yield

$$\frac{\delta n_i}{n_0} = \frac{\omega_1}{\omega} \frac{c_s^2\left(k_y^2 - \partial^2/\partial x^2\right)}{\omega_1^2 - \Omega_i^2} \psi \tag{7}$$

and

$$\frac{\delta n_e}{n_0} = \left(1 - i \frac{\nu_e \omega_2}{k_z^2 v_e^2}\right)^{-1} \psi \equiv \Gamma \psi \tag{8}$$

where, $\omega_1 = \omega + i\nu_{in}$, $c_s^2 = T_e/m_i$, $v_e^2 = T_e/m_e$, $\nu_e = \nu_{en} + \nu_{ei}$, $\psi = e\delta\phi/T_e$ and $\omega_2 = \omega - k_z V_0(x)$.

In deriving (7) and (8) we have made several simplifying assumptions. The ion temperature is neglected $\left(T_i = 0\right)$, parallel ion motion is neglected $\left(\omega \gg k_z c_s\right)$, $k_\perp^2/k_z^2 \gg \nu_e^2/\Omega_e^2$ is assumed, and the electrostatic assumption is used $(\delta E = -\nabla\delta\phi)$. We further make use of the quasi-neutrality assumption $\left(\delta n_i = \delta n_e\right)$ to derive the nonlocal mode structure equation. From (7) and (8) we find that

$$\frac{d^2\psi}{d\hat{x}^2} + Q(\hat{x})\psi = 0 \tag{9}$$

where

$$Q(\hat{x}) = \left[-\hat{k}_y^2 + \frac{\hat{\omega}}{\omega_1}\left(\hat{\omega}_1^2 - 1\right)\Gamma\right], \tag{10}$$

Γ is defined in (8), and we have written the variables in the following dimensionless form: $\hat{\omega} = \omega/\Omega_i$, $\hat{x} = x/\rho_s$, $\hat{\omega}_1 = \hat{\omega} + i\hat{\nu}_{in}$, $\hat{\omega}_2 = \hat{\omega} - \hat{k}_y\hat{V}_0$, $\hat{\nu}_\alpha = \nu_\alpha/\Omega_\alpha$, $\rho_s = c_s/\Omega_i$, $\hat{k}_y = k_y\rho_s$, $\hat{k}_z = k_z\rho_s$, $d = L_w/\rho_s$, $\hat{V}_0 = V_0/c_s$, and $\hat{V}_0(\hat{x}) = \hat{V}_0(1 - \hat{x}^2/d^2)$. For convenience, we will drop the caret over the symbols.

III. ANALYTICAL AND NUMERICAL RESULTS

We solve (9) numerically for the parameters appropriate for the auroral ionosphere and obtain the nonlocal growth rate of the collisional ion-cyclotron modes modified by finite current channel width effects. Before presenting these results, we first present approximate analytic solutions of (9). For $k_z^2 \gg \nu_e\omega_2$, we write (9)

$$\frac{d^2\psi}{dx^2} + [B - C\,x^2]\psi = 0 \tag{12}$$

where

$$B = [-k_y^2 + \frac{\omega}{\omega_1}(\omega_1^2 - 1)\{1 + i\,\frac{\nu_e\omega_2}{k_z^2}\}] \tag{13}$$

$$C = -i\,\frac{\omega}{\omega_1}(\omega_1^2 - 1)\,\frac{\nu_e V_0}{k_z d^2}$$

Equation (12) is of the form of Weber's equation which has solutions determined in terms of Hermite's functions. The eigenvalue is determined from

$$B^2 = (2m + 1)C \tag{14}$$

where m = 0, 1, 2, ... is the mode number. For m = 0 mode, we find that

$$\omega_1^2 - 1 = k_y^2\{1 - i \frac{\nu_e}{k_z^2} \omega_2)\}\Delta \qquad (15)$$

where

$$\Delta = [1 + \frac{1-i}{\sqrt{2}\, d} \frac{\{(\omega_1^2 - 1) \frac{\omega}{\omega_1} \frac{\nu_e V_0}{k_z}\}^{1/2}}{k_y^2}] \frac{\omega_1}{\omega} \qquad (16)$$

For $d = L_w/\rho_s \to \infty$, $\Delta = \omega_1/\omega$ and (15) reduces to the usual dispersion relation for the infinite current channel width case

$$\omega_1^2 = 1 + k_y^2 \{1 - i \frac{\nu_e \omega_2}{k_z^2}\} \frac{\omega_1}{\omega} . \qquad (17)$$

Writing $\omega = \omega_r + i\gamma$, with $|\gamma| < \omega_r$, one obtains the real frequency and growth rate expressions for the case of linear current driven collisional ion-cyclotron instability in the local approximation,

$$\omega_r = (1 + k_y^2)^{1/2} \qquad (18)$$

and

$$\gamma = \frac{k_y^2}{2k_z^2} \nu_e (\frac{V_0 k_z}{\omega_r} - 1) - \nu_{in} \qquad (19)$$

Physically, the instability arises due to the Doppler effect caused by parallel electron streaming. This results in wave growth via electron dissipation (ν_e) when the electron drift speed exceeds the parallel wave phase velocity [Chaturvedi and Kaw, 1975].

The nonlocal growth rate is given by [from (15)]

$$\gamma = \frac{k_y^2}{2\omega_r}\left[\frac{\nu_e\omega_r}{k_z^2}\left(\frac{k_zV_0}{\omega_r} - 1\right) - \frac{1}{\sqrt{2}\,d}\,\frac{\left\{\left(\omega_r^2 - 1\right)\frac{\nu_eV_0}{k_z}\right\}^{1/2}}{k_y^2}\right] \tag{20}$$

where we have assumed $\nu_{in} = 0$ for simplicity. The condition for marginal stability $(\gamma = 0)$ is therefore, approximately,

$$d = \frac{L_w}{\rho_s} \approx \left[\frac{\omega}{\sqrt{2}\,V_0k_z}\,\frac{k_z^2}{\nu_e\omega_r}\,\frac{\left\{\left(\omega_r^2 - 1\right)\frac{\nu_eV_0}{k_z}\right\}}{k_y^2}\right] \tag{21}$$

For $\hat{V}_0 \sim 30$, $\hat{\nu}_e = 10^{-3}$, $\hat{k}_y \sim 0.5$, $\nu_{in} \sim 0$, one finds $L_w \approx 4\rho_s$.

We note that a similar stabilization criterion was also obtained by Bakshi et al. [1983] for the collisionless ion cyclotron instability. The physical interpretation of the stabilization of the mode due to the finiteness of current channel width is as follows. The finite current channel profile considered here has a maximum value of V_0 and tends to $V_0 \to 0$ at $|x| \to d$. The nonlocal growth rate is the mode growth due to all the regions of $V_0(x)$ that are sampled by the wave packet, and is zero for $|x| > d$. Clearly, the growth rate obtained in the finite width channel case is reduced from the case in which the current sheet would be infinite at its peak value, V_0. Thus, the wave packet "sees" an effectively reduced electron drift speed in the finite-width current channel case, and, for sufficiently narrow channels, this 'effective' drift speed may not be large enough to exceed the parallel wave phase speed so that the mode is stabilized.

The nonlocal wave equation (14) was solved numerically for parameters appropriate to the auroral ionosphere. The growth rate (γ) was computed as a function of the half-width of the current-channel (L_W). Figures 2-5 show the behavior of the nonlocal growth rate of the current-driven collisional ion-cyclotron instability for various parametric dependences. For all the cases considered, the transverse wavelength was chosen such that $k_y \rho_s = 0.5$ and the parallel wavelength was chosen corresponding to the maximum growth rate. In Fig. 2 we plot γ/Ω_i versus L_W/ρ_s for $\nu_e/\Omega_e = 10^{-3}$ and $\nu_{in} = 0$, and two drift velocities, $V_0/c_s = 20$ and 30. We find that for larger drift velocities, complete stabilization occurs for narrower channels, or in other words, the instability persists for smaller width-channels than in the case of smaller drift velocity. Figure 3 depicts the dependence of the γ/Ω_i versus L_W/ρ_s as a function of electron collision frequency (ν_e) for $V_0/c_s = 30$ and $\nu_{in} = 0.0$. Since the instability is resistive in nature, the growth rates are higher for larger collisional frequencies. Therefore, for mode stabilization, the higher the electron collision frequency the narrower the channel-width required. The effect of ion collisional-damping is illustrated in the Fig. 4 where we plot γ/Ω_i versus L_W/ρ_s for $V_0/c_s = 30$ and $\nu_e/\Omega_e = 10^{-3}$ and several values of ν_{in}/Ω_i. The inclusion of the ion-damping introduces a threshold value for the electron drift velocity for the instability which is larger than the parallel phase velocity of the mode. Thus, in the presence of ion collisions, the mode can become stabilized for wider current-channels than in the case when $\nu_{in} = 0$. Finally, in Fig. 5 we plot γ/Ω_i versus L_W/ρ_s for different mode numbers for the parameters $\nu_{in} = 0$, $\nu_e/\Omega_e = 10^{-3}$, $V_0/c_s = 30$. The lowest order mode ($m = 0$) has the largest growth rate and higher modes have decreasing growth rates. Thus, the higher order modes are

stabilized for wider current-channels compared to the m = 0 mode. We note that the stabilization width is $L_w/\rho_s \approx 4$ in Fig. 5, which is in agreement with the current-channel-width computed for stabilization from the analytic expression (21).

IV. DISCUSSION

We find that the finite transverse width of a current-channel has an overall effect of reducing the growth rate of the collisional current driven ion cyclotron instability from the value obtained in the local approximation, and for sufficiently narrow channels can stabilize the instability. For typical auroral ionosphere parameters, i.e., $V_0/c_s \approx 30$, $\nu_e/\Omega_e \sim 10^{-3}$, $\nu_i/\Omega_i \sim .02$, it seems that the complete stabilization of the instability can occur for current-channel widths $L_w/\rho_s \lesssim 25$ (or $L_w \lesssim 250$ m since $\rho_s \sim 10$ m). Observations indicate that the currents often flow in sheets with thicknesses in ionosphere on the order of ~ km [Burke et al., 1982]. Thus, it is possible that this instability may still be operative in ionospheric situations provided the currents are intense enough (so that the electron drift velocity is above the threshold level). These results are qualitatively similar to those of Bakshi et al. [1983] who considered the case of current driven collisionless ion-cyclotron instability.

There are some recent laboratory experiments on the excitation of ion-cyclotron instability by a field-aligned current [Cartier et al., 1985]. By varying parameters, one may be able to scan the domain of current driven EIC instability in the collisionless and collisional domain in these experiments and thus check the results of the present work (collisional domain) vis-a-vis the work of Bakshi et al. [1983] (collisionless domain). We note that the theoretical treatment of both these domains for the current-driven EIC instability has been recently carried out in the local approximation by Satyanarayana et al. [1985].

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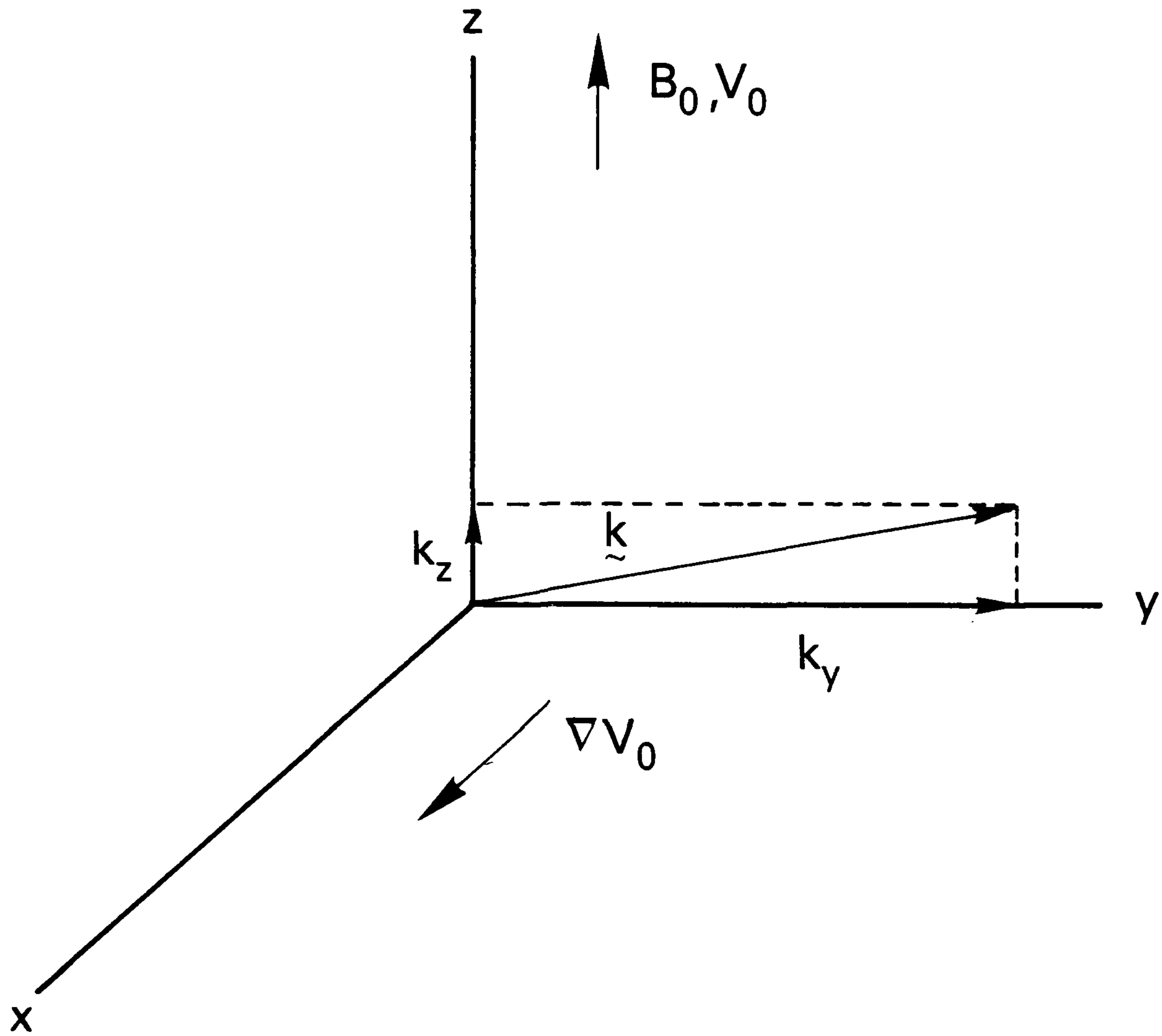

Fig. 1 Slab geometry used in the analysis.

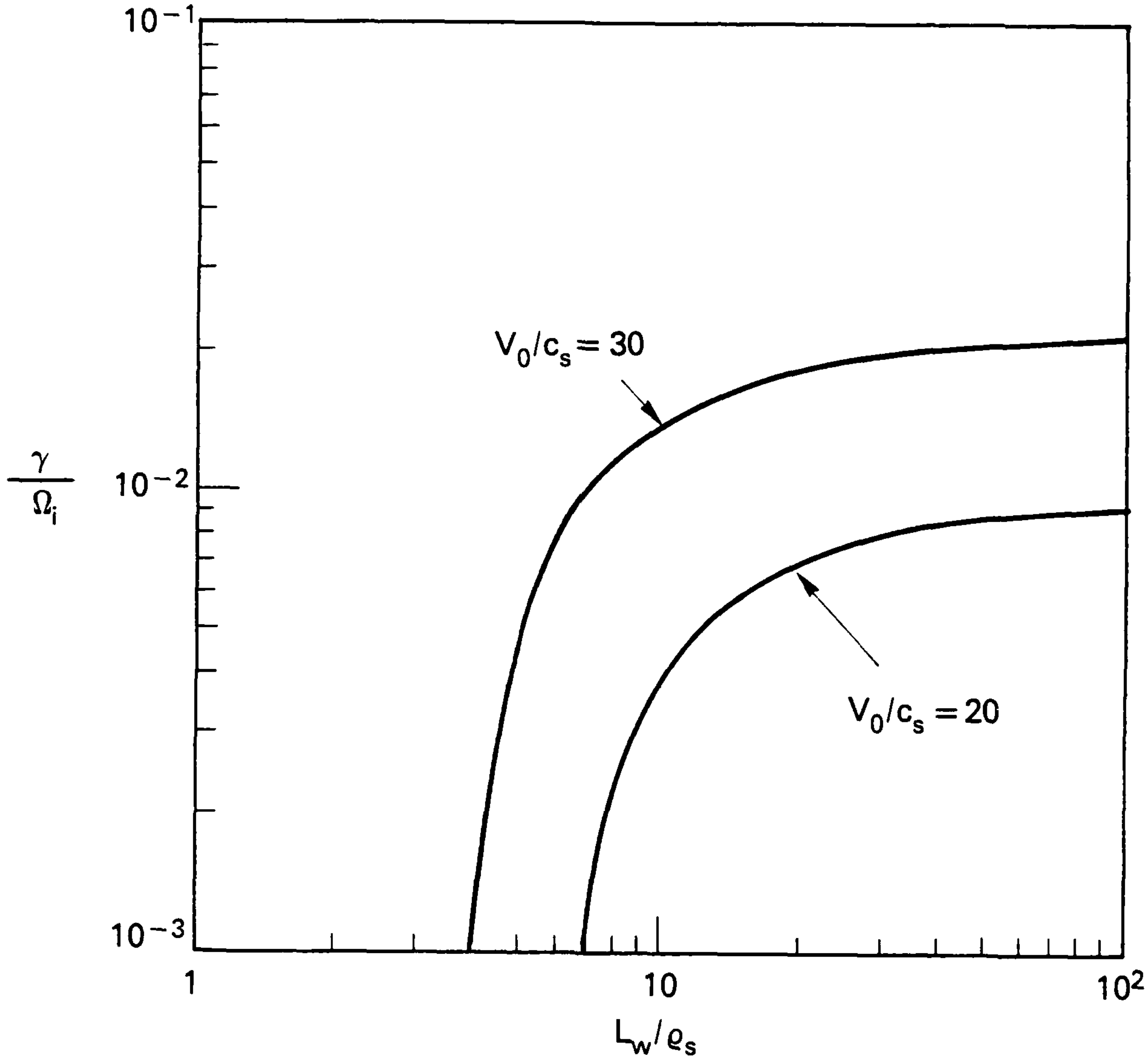

Fig. 2 Plot of γ/Ω_i vs. L_w/ρ_s for $\nu_e/\Omega_e = 10^{-3}$, $\nu_{in}/\Omega_i = 0$ and V_0/c_s = 20 and 30. Although plotted on a log-log scale, we remark that the modes are actually stabilized (i.e., $\gamma < 0$) for values of L_w/ρ_s slightly less than those for which $\gamma/\Omega_i = 10^{-3}$.

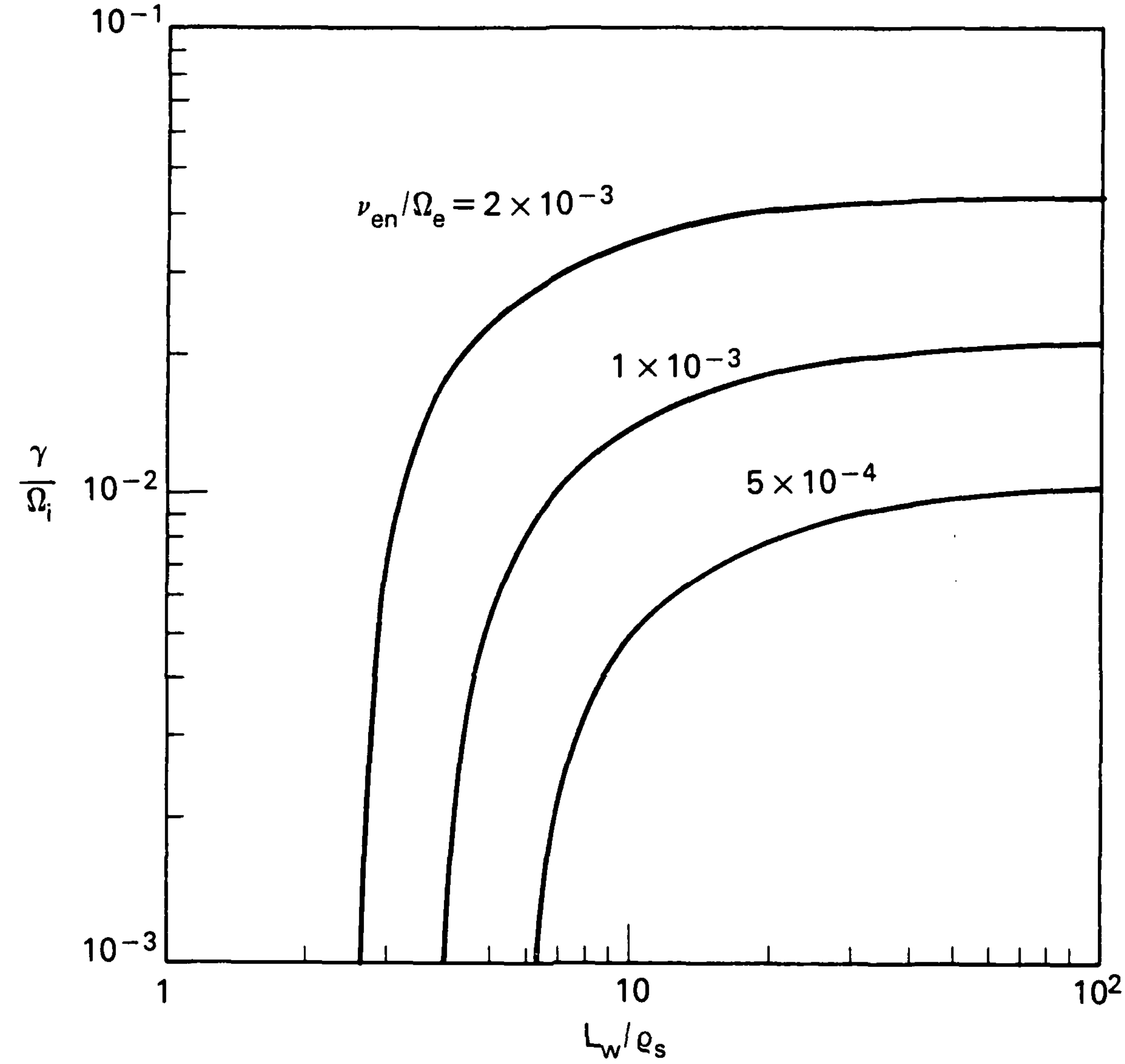

Fig. 3 Plot of γ/Ω_i vs. L_w/ρ_s for $\nu_{in}/\Omega_i = 0$, $V_0/c_s = 30$ and $\nu_e/\Omega_e = 2\times10^{-3}$, 1×10^{-3}, and 5×10^{-4}.

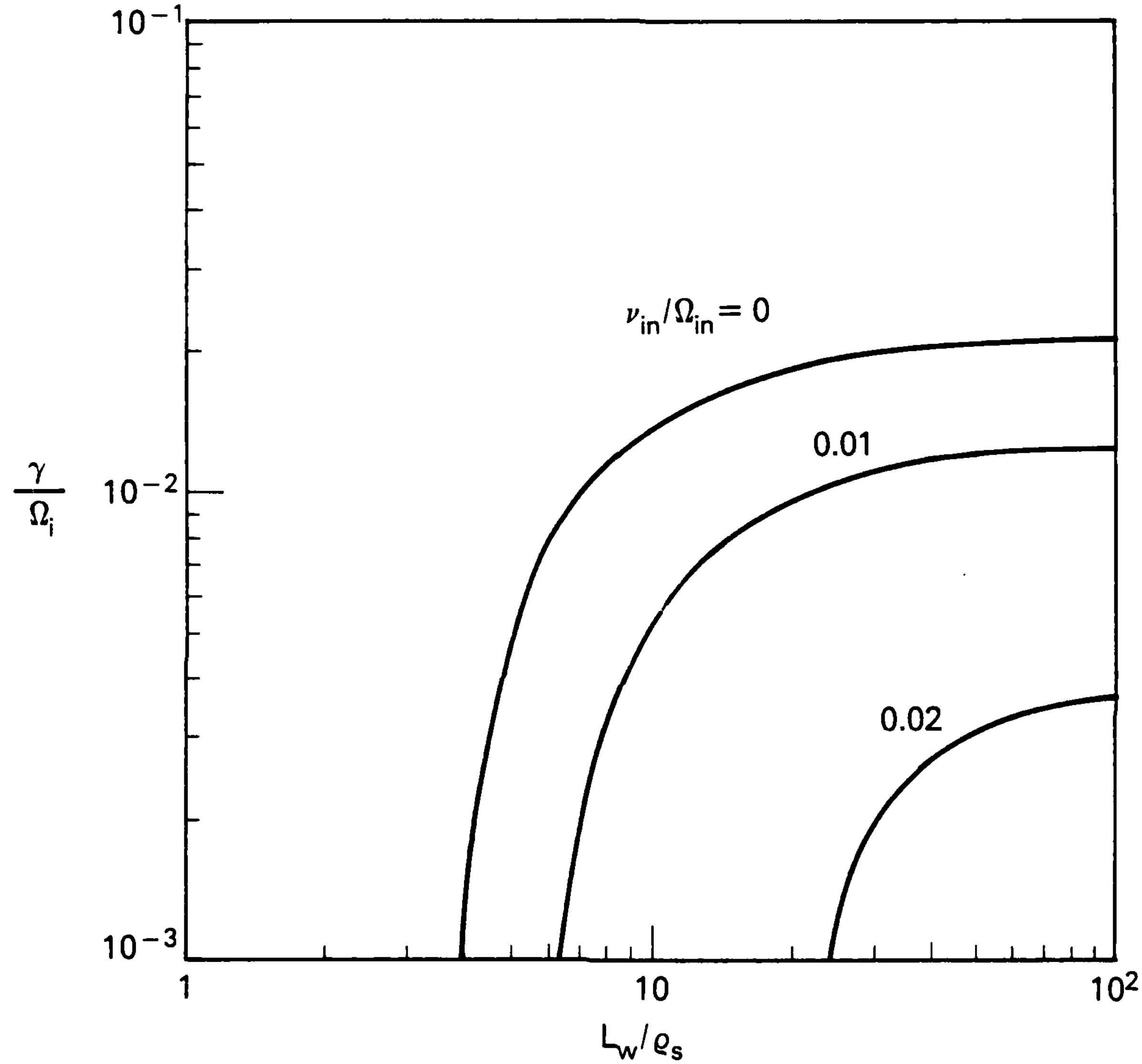

Fig. 4 Plot of γ/Ω_i vs L_w/ρ_s for $\nu_e/\Omega_e = 10^{-3}$, $V_0/c_s = 30$ and $\nu_{in}/\Omega_i =$ 0, 0.01, and 0.02.

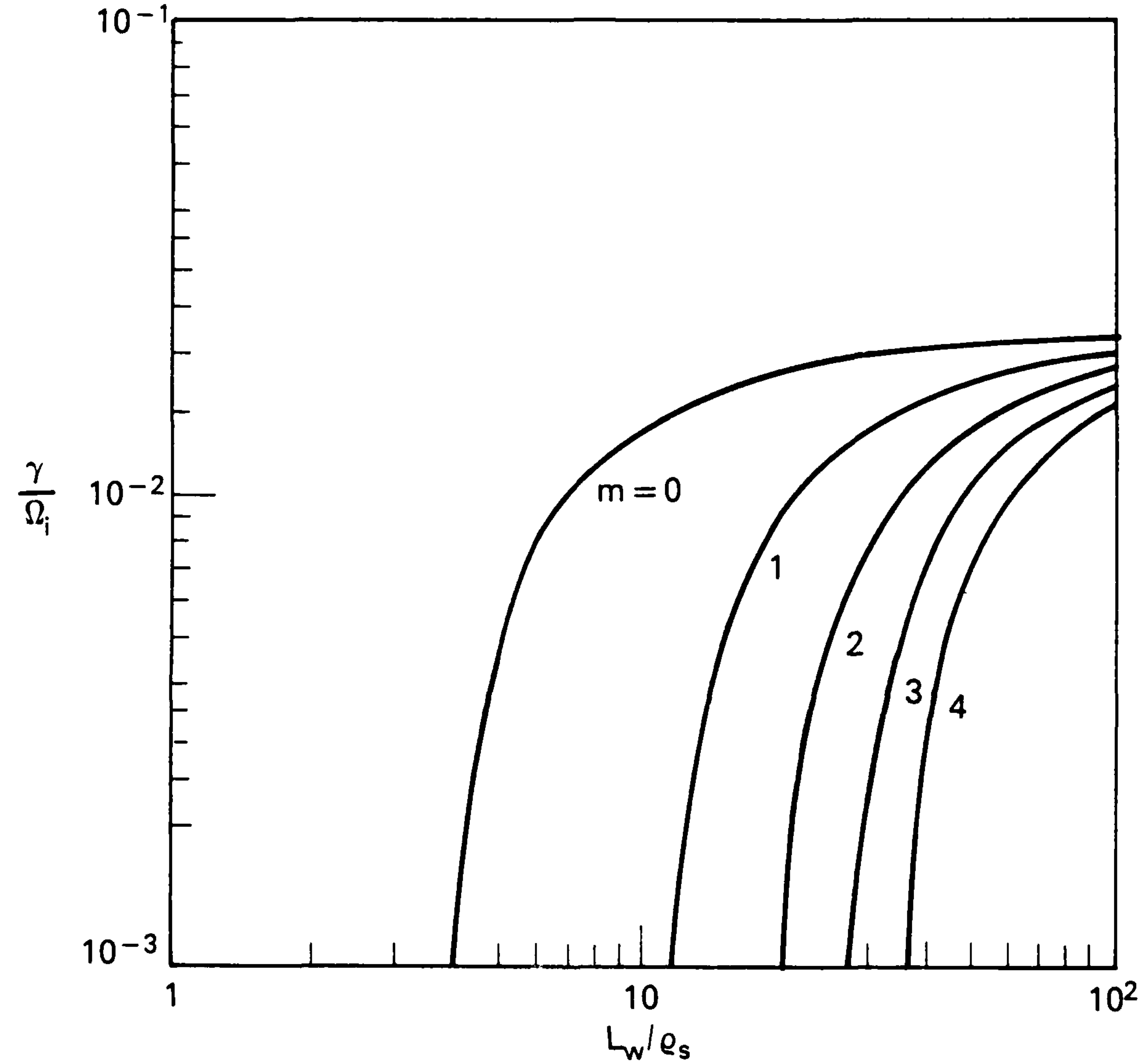

Fig. 5 Plot of γ/Ω_i vs. L_w/ρ_s for $\nu_e/\Omega_e = 10^{-3}$, $\nu_{in}/\Omega_i = 0$, $V_0/c_s = 30$, and m = 0, 1, 2, 3, and 4.

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